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Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review

Luisa F. Cabeza [a,*], Lídia Rincón [a], Virginia Vilariño [b], Gabriel Pérez [a], Albert Castell [a]

[a] GREA Innovació Concurrent, Universitat de Lleida, Edifici CREA, Pere de Cabrera s/n, 25001 Lleida, Spain
[b] Business Council for Sustainable Development, Buenos Aires, Argentina

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ABSTRACT

This review summarizes and organizes the literature on life cycle assessment (LCA), life cycle energy analysis (LCEA) and life cycle cost analysis (LCCA) studies carried out for environmental evaluation of buildings and building related industry and sector (including construction products, construction systems, buildings, and civil engineering constructions). The review shows that most LCA and LCEA are carried out in what is shown as “exemplary buildings”, that is, buildings that have been designed and constructed as low energy buildings, but there are very few studies on “traditional buildings”, that is, buildings such as those mostly found in our cities. Similarly, most studies are carried out in urban areas, while rural areas are not well represented in the literature. Finally, studies are not equally distributed around the world.

Contents

* Corresponding author. Tel.: +34 973 00 35 76; fax: +34 973 00 3575.
E-mail addresses: lcabeza@diei.udl.cat (L.F. Cabeza), mvilarino@ceads.org.ar (V. Vilariño).

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1. Introduction

As we know today's world is facing major environmental problems i.e. global warming, ozone layer depletion, waste accumulation, etc. Over the last few decades the research indicates that the global climate is changing rapidly [1,2] and also un-reveals the fact that this change will continue with time [3]. So there is an urgent need to mitigate these undesirable problems arising from our modern way of lifestyle to save our environment and our world.

Buildings play an important role in consumption of energy all over the world. The building sector has a significant influence over the total natural resource consumption and on the emissions released. A building uses energy throughout its life i.e. from its construction to its demolition. The demand for energy in buildings in their life cycle is both direct and indirect. Direct energy is used for construction, operation, renovation, and demolition in a building; whereas indirect energy is consumed by a building for the production of material used in its construction and technical installations [4].

The social, economic and environmental indicators of sustainable development are drawing attention to the construction industry, which is a globally emerging sector, and a highly active industry in both developed and developing countries [5,6].

Life cycle assessment (LCA) methods have been used for environmental evaluation of product development processes in other industries for a long time, although application to the building construction sector is stated of the art for the last 10 years [7,8]. Because LCA takes a comprehensive, systemic approach to environmental evaluation, interest is increasing in incorporating LCA methods into building construction decision making for selection of environmentally preferable products, as well as for evaluation and optimization of construction processes [9]. In addition, a growing body of literature is developing, employing LCA methods in performance evaluation of buildings, their design, and construction practices. However, this LCA literature is fairly fragmented and spread over several national and international publications.

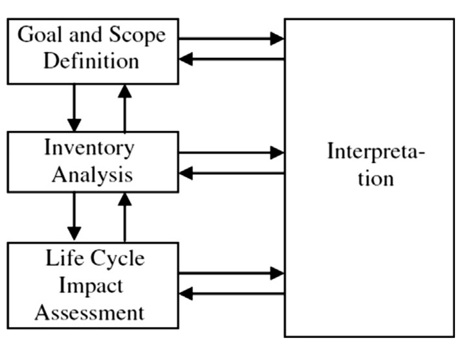

Fig. 1. LCA framework based on ISO 14040 [14].

This review tries to organize and to complete the existing literature about LCA applied on the building sector, following and completing different classifications found in the literature:

1. Life cycle assessment in the building industry [5,7]:
   - LCA applications for construction products selection
   - LCA applications for construction systems/process evaluation
   - LCA tools and databases related to the construction industry
   - LCA methodological developments related to the construction industry
2. Life cycle assessment of buildings and the building sector [5,7,8]:
   - LCA of residential buildings
   - LCA of non-residential buildings
   - LCA of civil engineering constructions

In addition to the LCA concept, there are other approaches for assessing the environmental impact of buildings.

One of them is the named life cycle energy analysis (LCEA). LCEA is an approach in which all energy inputs to a product are accounted for, not only direct energy inputs during manufacture, but also all energy inputs needed to produce components, materials and services needed for the manufacturing process. This methodology is applied to several studies found in the literature [10]. This review includes LCEA in the literature, LCE results, low energy buildings, and LCEA by construction type.

Also life cycle cost analysis (LCCA) of buildings has been carried out by several researchers [11] and is included here. LCCA is a method for assessing the total cost of facility ownership; it takes into account all costs of acquiring, owning, and disposing of a building or building system.

2. Definitions

2.1. Life cycle assessment

Life-cycle assessment is a tool for systematically analyzing environmental performance of products or processes over their entire life cycle, including raw material extraction, manufacturing, use, and end-of-life (EOL) disposal and recycling. Hence, LCA is often considered a "cradle to grave" approach to the evaluation of environmental impacts [12,13].

The concept of life cycle studies has been developed over the years, mainly in the 70s and 80s. Moreover, life cycle studies had focused on the quantification of energy and materials used and wastes released into the environment throughout the life cycle [2].

The International Organization for Standardization (ISO) adopted an environmental management standard in the 1990s as part of its 14,000 standards series, with the 14,040 series focusing on establishing methodologies for LCA [14,15]; similar approaches

Table 1
Definitions of LCA [14,15,17].

Acronym	Concept	Definition
LCA	Life cycle assessment	Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle
LCI	Life cycle inventory analysis	Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle
LCIA	Life cycle impact assessment	Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product
–	Life cycle interpretation	Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations
ILCD	International reference life cycle data system	ILCD consists of the ILCD Handbook and the ILCD Data Network. It provides governments and businesses with a basis for assuring quality and consistency of life cycle data, methods and assessments

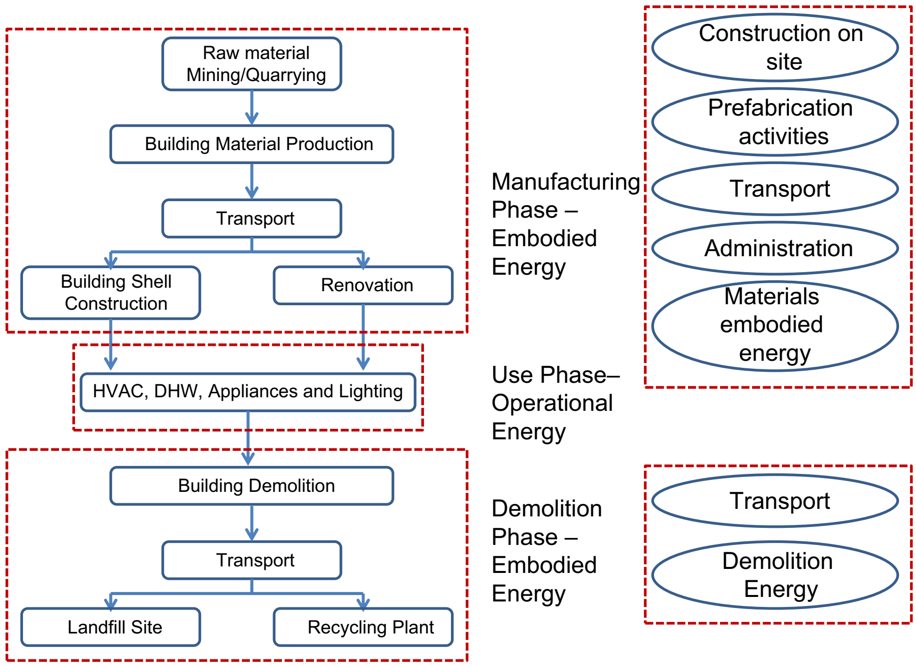

Fig. 2. Life cycle energy of a building. Adapted from Ramesh at al. [10] and Dixit et al. [22].

have been adopted by other international organizations [16,17]. A major facet of the ISO standard is a four-stage iterative framework for conducting LCA analyses. The four steps include: goal and scope definition; inventory analysis; life-cycle impact assessment (LCIA); and interpretation (Fig. 1 and Table 1).

The goal and scope definition establishes the functional unit, system boundaries, and quality criteria for inventory data. The life cycle inventory analysis deals with the collection and synthesis of information on physical material and energy flows in various stages of the products lifecycle. In the life cycle impact assessment these environmental impacts of various flows of material and energy are assigned to different environmental impact categories, the characterization factor is used to calculate the contribution of each of the constituents for different environmental impact categories (climate change, ozone depletion, ecotoxicity, human toxicity, photochemical ozone formation, acidification, eutrophication, resource depletion, and land use). Finally the life cycle interpretation deals with the interpretation of results from both the life cycle inventory analysis and life cycle impact assessment.

Life cycle assessment has been used in the building sector since 1990 [5,18,19] and has also been used to assess product development processes from cradle to grave for many years [2,7,10,14,20,21]. With the current push toward sustainable construction, LCA has gained importance as an objective method to evaluate the environmental impact of construction practices.

2.2. Life cycle energy analysis

Life cycle energy analysis is an approach that accounts for all energy inputs to a building in its life cycle [10]. The system boundaries of this analysis (Fig. 2) include the energy use of the following phases: manufacture, use, and demolition. Manufacture phase includes manufacturing and transportation of building materials and technical installations used in new building and renovation of the buildings. Operation phase encompasses all activities related to the use of the buildings, over its life span. These activities include maintaining comfort condition inside the buildings, water use, and powering appliances. Finally, demolition phase includes destruction of the building and transportation of dismantled materials to landfill sites and/or recycling plants.

Life cycle energy includes [10]:

- Embodied energy: Energy content of all the materials used in the building and technical installations, and energy incurred at the time of new construction and renovation of the building.
- Operating energy: Energy required for maintaining comfort conditions and day-to-day maintenance of the buildings. Energy for HVAC (heating, ventilation and air conditioning), domestic hot water, lighting, and for running appliances.
- Demolition energy: Energy required at the end of the buildings′ service life to demolish it and to transport the material to landfill sites and/or recycling plants.

2.3. Life cycle cost analysis

The National Institute of Standards and Technology (NIST) Handbook 135, 1995 edition [23], defines life cycle cost (LCC) as “the total discounted dollar cost of owning, operating, maintaining, and disposing of a building or a building system” over a period of time. Life cycle cost analysis is an economic evaluation technique that determines the total cost of owning and operating a facility over a period of time [24].

Life cycle cost analysis can be performed on large and small buildings or on isolated building systems. Many building owners apply the principles of life cycle cost analysis in decisions they make regarding construction or improvements to a facility.

3. Life cycle assessment in the building industry

3.1. LCA applications for construction products selection

Following in the footsteps of traditional LCA product evaluation applications, several studies have focused on the environmental evaluation of building materials. The objective of such research efforts is to enable selection of environmentally preferred materials

and products by identifying sources of the most significant environmental impacts [7]. Some of these studies are summarized below.

Jönsson et al. [25] compared environmental impacts from production of three flooring materials (linoleum, vinyl flooring and solid wood flooring) in Sweden using process based LCA and data from local suppliers. Solid-wood flooring was found to be environmentally preferable over linoleum and vinyl options. The authors stressed the need to assess maintenance (use phase) and landfill (end-of-life phase) impacts to develop a more comprehensive understanding.

Asif et al. [26] conducted process-based LCA for materials used in residential construction in Scotland. They assessed the production phase for five commonly used residential construction materials (wood, aluminum, glass, concrete and ceramic tiles) from the energy use and air emissions standpoint. Concrete was found to account for over 60% of the total embodied energy.

Similarly, Ximenes and Grant [27] quantified the greenhouse benefits of the use of wood products in Australia, in comparison with alternative building materials. The LCA gave best results when the original floor and sub-floor products were substituted by timber wood.

Koroneos and Dompros [28] studied the brick production process in Greece, using data from a local brick production plant and from published literature, to identify possible areas for improvement from the environmental perspective. The authors included recycling of bricks within the analysis but excluded the construction, use, and disposal phases. Using the Eco-indicator 95 aggregation method, analysis showed that acidification contributed more than half of the total environmental impact. The authors recommended use of low-sulfur fuels to reduce such impact.

Wu et al. [29] discussed the life-cycle environmental impacts of various kinds of cement and steel used in the Chinese building industry using a “green tax-based weighting” approach. Esin [30] presented a point-based weighting approach and used it to evaluate environmental impacts caused by production of several building materials in Turkey. Further information on weighting methodologies in LCA can be found in [31].

Other examples of LCA studies of building materials and products include floor covering in Germany [32]; comparison of ceramic and marble tiles in Italy [33]; comparison of bamboo with steel and wood in western Europe [34]; and the use of nano-sized titanium dioxide coating in glass [35].

Recently, a review on the environmental impact and LCA of traditional and “green” concretes was published [36]. They studied the variances in the results depending on the inventory analysis, the impact analysis, and in the interpretation phase. They concluded that all decisions made during the LCA (functional unit choice, LCA system boundaries, inventory data, choice of the impact assessment method, etc.) influence greatly the LCA results, and therefore, the environmental value of a material, in this case traditional concrete or “green” concrete.

Finally, phase change materials (PCM) inclusion in buildings has been assessed using LCA. de Gracia et al. [37] evaluated the environmental impact of including PCM in a typical Mediterranean building—with traditional brick and an air chamber as envelope construction system, using measured operational energy savings in an experimental set-up. Results showed that the addition of PCM (paraffin and salt hydrate) in the building envelope, although decreasing the energy consumption during operation, did not reduce significantly the global impact throughout the lifetime of the building. For the hypothetical scenario considering summer conditions all year around and a lifetime of the building of 100 years, the use of PCM reduced the overall impact by more than 10%. Moreover, salt hydrates are more environmentally friendly than paraffins as PCM. Later on, Castell et al. [38] verified that, when incorporating PCM in building envelopes, its use for energy savings must be maximized in order to compensate its manufacturing impact. Rincón et al. [39] extended the study use not only LCA but also mass flow analysis (MFA) to assess the sustainability of the new construction system. MFA results showed the significant quantity of natural resource extraction required for building which leads to a considerable ecological rucksack; while LCA results showed the importance of the operational phase of the building in the overall building energy consumption, and therefore in the environmental impact.

LCA was also used to evaluate the environmental impact produced during the manufacturing and disposal phase by highlighting and comparing the effect of using different building materials, insulating materials, and PCM [40,41]. The construction systems evaluated were based on conventional bricks, alveolar bricks, and precast concrete panels. The PCM used were paraffins, salt hydrates and esters. The authors concluded that embodied energy is responsible of most of the environmental damage, requiring natural materials with similar technical characteristics than conventional ones.

Aranda-Usón et al. [42] carried out a theoretical LCA analysis of the use of PCM in buildings also in Spain. The main results concluded that the use of PCM can reduce the overall energy consumption and the environmental impacts, but that this reduction is strongly influenced by the climate conditions and the PCM introduced.

Also acoustic insulation materials have been assessed with LCA. Asdrubali et al. [43] carried out a survey on acoustical properties of sustainable materials, both natural and recycled. Considered natural materials are hemp, kenaf, coco fiber, sheep wool, wood wool, cork, cellulose, and flax; traditional materials are glass wool, rock wool, and expanded polystyrene. Considered recycled materials are rubber, plastic, textile fibers, and solid wastes. Finally, also mixed and composites are considered in this study (for example, wood-plastic composite – WPC – high density polyethylene/polypropylene—HDPE/PP, or sandwich panels made of coconut fibres, foam and fabric). Asdrubali [44] claims that LCA on entire buildings show that the substitution of conventional thermal and sound insulating materials with sustainable ones has significant effects on the impact of all the various phases of the life of the building.

3.2. LCA applications for building systems and construction processes evaluation

Evaluation of environmental impacts of construction and buildings involves more than the simple aggregation of individual product and material assessments [8]. Consequently, several studies have attempted to assess complete buildings, building systems, and construction processes. These efforts have often identified life-cycle phases with the highest environmental impacts and have provided a basis for overall building system assessment.

Citherlet and Defaux [45] presented a process-based life cycle assessment of three home designs in Switzerland. They classified life-cycle environmental impacts into direct and indirect categories; direct impacts included all use-related energy consumption impacts; and indirect impacts included other upstream and downstream impacts from material extraction, production, construction, demolition, etc. Their results show that direct environmental impacts can be significantly reduced by better insulation and by the use of renewable energy sources. Fay et al. [46] conducted a study of single-family residences using life-cycle assessment and life-cycle cost analysis (LCCA). This paper briefly explains some of the theoretical issues associated with life-cycle energy analysis and then uses an Australian based case study to demonstrate its use in evaluating alternative design strategies for an energy efficient residential building. For example, it was found that the addition of higher levels of insulation in Australia paid

back its initial embodied energy in life-cycle energy terms in around 12 years. However, the saving represented less than 6% of the total embodied energy and operational energy of the building over a 100-year life cycle. This indicates that there may be other strategies worth pursuing before additional insulation. Energy efficiency and other environmental strategies should be prioritized on a life-cycle basis.

While the above studies analyzed whole buildings, some studies have focused on building subsystems. For example, Osman and Ries [47] used the process-based LCA framework to evaluate environmental impacts of construction and operations of a cogeneration facility for meeting the energy requirements of a commercial building. They conducted energy simulations to determine the building's energy needs throughout the year. The authors concluded that certain cogeneration facilities might be environmentally preferable over conventional energy production facilities. Glick [48] analyzed two heating system solutions for a home in Colorado—a gas forced-air system (GFA) and a solar radiant system (SRS). The analysis covered both environmental LCA and LCCA. The study considered energy use and global warming potential (GWP) as the environmental performance indicators and assessed these for manufacturing, construction, use and maintenance, and disposal phases. Life-cycle cost analysis was performed for the manufacturing and use and maintenance phases. Results suggested that the GFA system is both environmentally and economically preferable to SRS, but a hybrid solution incorporating a gas-fired boiler in the SRS is an overall optimum choice.

O'Brien et al. [49] conducted comparative LCA of deconstruction methods for military barracks, using SimaPro modeling software. They analyzed four scenarios with varying degrees of manual and traditional mechanical deconstruction and post-deconstruction material reuse. Materials salvaged using either 100% or 44% manual deconstruction and reused within a 32 km radius of the deconstruction site yielded the most favorable environmental and health impacts. The significant impacts involved in the life cycle of diesel fuel required for transportation emphasize the need for developing reuse strategies for deconstructed materials at the regional level.

While all the above-mentioned studies used a process LCA approach, Ochao Franco [50] employed economic input–output based life cycle assessment methods for evaluating three case study residences in Pennsylvania, Texas, and Michigan. Similar to Keoleian et al. [51], these results also clearly highlighted the dominance of the building use phase. The use phase accounted for over 90% of energy use, electricity use, fossil fuel depletion, and human-health impact categories, and for over 50% of ore depletion, global warming effects, soil toxicity, and air pollution. They compared their results for the Ann Arbor case study with process LCA results from Keoleian et al. [51] and found that estimated impacts were larger with the use of economic input–output based LCA (EIO-LCA) methods, owing to the inclusion of indirect effects.

Muga et al. [52] estimated and compared the economic and environmental impacts of a green roof with a built-up roof using EIO-LCA methods. Their environmental impact analysis indicated that a green roof emits three times more environmental pollutants than built-up roofs in the material acquisition life stage. However, in the use and maintenance life stage, a built-up roof emitted three times more pollutants than a green roof. Overall, when emissions from both the material acquisition life stage and the use and maintenance life stage were combined, the built-up roof contributed 46% more environmental emissions than a green roof over a 45-year building life span. Life-cycle cost results using Monte Carlo simulations indicated that a green roof costs approximately 50% less to maintain over a 45-year building life than a built-up roof.

Rincón et al. [53] compared green roofs with recycled rubber and puzolana gravel as drainage layer with conventional roofs using the EcoInvent 99 (EI99) LCA methodology. The operational phase was obtained from real measured data from experimental buildings considering heating and cooling energy consumptions in winter and summer period, respectively. Green roofs, both with puzolana and recycled rubber as drainage layer, had lower energy consumption than a conventional roof in summer conditions. Both had similar impact points in the operational phase, but puzolana had a lower disposal impact than recycled rubber crumbs. Nevertheless, the improvement of recovering a waste material such as recycled rubber is not still available in the manufacturing impact points given by EI99.

Radhi and Sharples [54] assessed the impact of different facades parameters on global warming with a clear focus on materials, local materials when possible. Five facade scenarios are assessed, consisting of different layers and materials. The study concluded that the most effective measures for reducing the CO_2 emissions is the reduction of emission rates of concrete blocks.

Guggemos and Horvath [55] proposed an augmented process-based hybrid LCA model – the Construction Environmental Decision Support Tool (CEDST) – to analyze the environmental effects from the construction phase of commercial buildings as applied to a California building. The authors argued that significantly larger use-phase effects often overshadow the construction phase in building LCA. However, such construction-phase effects, when aggregated at the national level, may prove to be significant. CEDST evaluates environmental effects from the manufacture of temporary materials used in the construction process (e.g., formwork), transportation of materials and equipment, equipment use, and waste generation during construction. In the case study, equipment use accounted for about 50% of environmental effects, while temporary construction materials had the second largest impact on the environment.

Bilec et al. [56] also applied an augmented process-based hybrid LCA model to evaluate construction-phase environmental impacts of a precast parking garage in Pittsburgh, Pennsylvania. Environmental impacts caused by transportation, equipment use, construction service sectors, production and maintenance of construction equipment, as well as on-site electricity usage and water consumption were assessed. Transportation had the largest impact in most categories. The authors recommended including environmental costs as social externals in bid evaluations when awarding construction contracts.

On the other hand, Kellenberger and Althaus [57] studied the relevance of simplifications in LCA of building components, concluding that the building process and the cutting waste could be neglected due to its low contribution to the global impact, while transports and ancillary were relevant.

There are very few studies that actually evaluate the retrofit of buildings, but in 2013, Ardente et al. [58] presented a study comparing six public buildings (or case studies) where retrofit actions had been implemented. The buildings studied were an old brewery (Brno, Czech Republic), the Hol timber church (Gol, Norway), a college building (Plymouth, UK), the Provehallen cultural center (Copenhagen, Denmark), a nursing home (Stuttgart, Germany), and a university building (Vilnius, Lithuania). The authors concluded that the most significant benefits related to energy savings and reduction of CO_2 emissions are mainly related to the improvement of the envelope thermal insulation. But substituting lighting and glazing components also provided significant energy benefits. On the other hand, both solar and wind plants involved lower energy savings and higher payback indices than predicted.

Vieira and Horvath [59] used LCA to assess the end-of-life impacts of buildings. This is achieved through different solutions, but most significantly through the use of hybrid LCA and the definition of allocation boundaries in a way that decreases the uncertainty associated with technological forecasting. This methodology is compared with traditional (attributional) LCA techniques. Attributional LCA aims

at describing the environmental properties of a life cycle and its subsystems, while consequential LCA aims at describing the effects of changes within the life cycle. Given the variance in the results between the ALCA (attributional LCA) and the (consequential LCA) CLCA analysis, which may be due to uncertainties in the models and data, neither approach appears to yield significantly more complete results than the other. The lower impact values reached with the CLCA are a result of the modeling of market behavior and the inclusion of recycling loops. This demonstrates the need to account for the supply chain and economy-wide impacts resulting from recycling and product substitution.

Rehl et al. [60] stated that many studies that apply LCA methodology avoid the differentiation between ALCA and CLCA. The focus of the ALCA approach lies on the analysis of environmental impacts of a product, a process or a system while the approach of the CLCA is to identify the technology affected by a change in demand. ALCA is also referred as "accounting", "average", "book-keeping", "descriptive", "non-marginal" or "retrospective method, while CLCA is also called "change-oriented", "market-based", "marginal" or "prospective" method. The review carried out by Mason Earles and Halog [61] only identified the use of ALCA/CLCA in building applications in Vieira and Horvath [59] described above.

3.3. LCA tools and databases related to the construction industry

A variety of construction-related software tools and databases provide standardized assessment models and inventory data at multiple scales [7,62,63]. The scales range from industry-wide and sector-wide data down to product- and even brand-specific data.

Trusty and Horst [64] suggested a three-tiered classification scheme for LCA related tools. These include:

(1) Level-1 product comparison tools such as BEES [65]; National Renewable Energy Laboratory's (NREL) U.S. Life-Cycle Inventory (LCI) Database [66]; SimaPro [67]; Ganzheitliche Bilanzierung Integrated Assessment [68]; and Life Cycle Explorer [69].
(2) Level-2 whole-building decision support tools like Athena Eco-Calculator [70]; Envest 2 [71]; and LCA in Sustainable Architecture [72].
(3) Level-3 whole-building assessment systems and frameworks, such as Athena Impact Estimator; BRE environmental assessment method [73]; and the LEED rating system [74].

Norris and Yost [69] draw a distinction between the Level-1 tools, which are focused on building material selection, and others, that are true life-cycle inventory modeling tools. LCI tools offer more transparency between model outcomes and input data than the building material selection systems. Erlandsson and Borg [75] note that most LCA tools – BEES, Athena, EcoQuantum, and Building Environmental Assessment Tool (BEAT) – take a bottom-up approach. In this approach, the software begins with the building materials themselves, assuming that the design stage has already taken place. Only the Envest 2 system takes a top-down approach by starting with the building shape, then moving through material specifications, and finally construction details. The new Athena EcoCalculator takes a more design-oriented approach to building material and assembly specification, allowing users to see the design impacts of material specification changes.

Haapio and Viitaniemi [62] summarized the environmental assessment tools developed for the building sector focusing on European and North American ones (Table 2). Most of the building environmental assessment tools have been developed by research institutes.

BEES is a building material specification tool used in the United States. It provides an integrated economic and environmental assessment package for a variety of preloaded building materials. Users apply functional weights to both economic and environmental portions of the analysis, as well as to a variety of damage categories. These weighting schemes, in turn, influence the performance score provided by the software. For the construction industry, BEES includes two desirable characteristics—the inclusion of integrated economic analysis, and an indoor air quality damage category. Lack of transparency may be considered as a shortcoming of BEES. A survey of BEES users identifies that builders, designers, and government entities find LCA tools that require less expert input easier to use, while 82% of respondents value transparency in an LCA tool [76].

Table 2
Building environment assessment tools assessed by Haapio and Viitaniemi [62].

Tool	Developer
ATHENA™ Experimental Impact Estimator	ATHENA Sustainable Material Institute, Canada
BEAT 2002	Danish Building Research Institute (SBI), Denmark
BeCost (previously known as LCA-house)	VTT, Finland
BEES 4.0	U.S. National Institute of Standards and Technology (NIST), USA
BREEAM	Building Research Establishment (BRE), UK
EcoEffect	Royal Institute of Technology (KTH), Sweden
EcoProfile	Norwegian Building Research Institute (NBI); Norway
Eco-Quantum	IVAM, The Netherlands
Envest 2	Building Research Establishment (BRE), UK
Environmental Status Model (Miljöstatus)	Association of the Environmental Status of Buildings, Sweden
EQUER	École de Mines de Paris, Centre d'Énergétique et Procédés, France
ESCALE	CTSB and the University of Savoie, France
LEED®	U.S. Green Building Council, USA
LEGEP® (previously known as Legoe)	University of Karlsruhe, Germany
PAPOOSE	TRIBU, France
TEAM™*	Ecobilan, France

* TEAM™ is a professional LCA-tool, to evaluate the life cycle, environmental and cost profiles of products and technologies, including buildings. It is the only tool cited in this paper that is not specifically for environmental assessment of buildings. However, it can be used for buildings, for example as product comparison tool and information resource.

GaBi is a process-based model, developed at the University of Stuttgart, Germany, that allows for life-cycle assessments that are ISO 14040-compliant [68]. It uses an integrated products database developed through industry reviews and technical literature. Economic cost integration is built into GaBi; however, use-phase impacts do not appear to be addressed thoroughly by this software package. Other generic Level-1 LCA software tools that also have information on common building materials include: SimaPro from The Netherlands and Tool for Environmental Analysis (TEAM) from France (TEAM) [67,77].

The Athena EcoCalculator considers whole-building assemblies, recognizing that changes in specifying one building material may have greater implications for other associated materials. The EcoCalculator also addresses two additional limitations of other LCA tools: life cycle inventory data availability and the establishment of reference values against which to measure building performance [64]. LCI data availability was addressed by the creation of a North American database within the application. The database was developed by a public–private partnership, and regional and national case studies have been established to provide reference values.

Envest 2 was developed as a building life-cycle design tool that allows an analyst to examine environmental and financial trade-offs and impacts during the building design process [71]. Designers begin by entering data related to building height, window area, and choices

of exterior assemblies such as walls and roof materials. The software then selects those components with the optimal overall environmental and economic impacts to allow the analyst to make trade-offs during the design stage. The model explicitly includes data from the building's use phase, including repair, maintenance, and replacement.

Norris and Yost [69] discuss Life-Cycle Explorer (LCE) software, designed in part to address two specific challenges for construction LCAs—that aspects of the use phase of building materials may be context-specific; and that the outcome of the LCA may rest on the building materials' service life. The authors propose the prototypical LCE model through a case study application. Strengths of the LCE software include the ability to make product comparisons and incorporate parameter and model uncertainty into the analysis.

LISA is a freely available streamlined LCA decision support tool for construction developed in Australia [72]. The LISA website [72] lists a number of case studies of building LCAs using the software. ECO-BAT [78] is another software tool available for conducting LCAs of buildings that has LCI information on over 100 generic construction materials, drawn from the ecoinvent Data database, and on various energy sources for Europe. Users can define their buildings by picking construction elements (walls, windows), choosing materials composition, and specifying an energy mix profile for heating, cooling, ventilation, etc.

Carnegie Mellon University's EIO-LCA model, an online tool, although not designed specifically for the construction industry, has, however, been used for life-cycle assessments of buildings and construction processes by approximating environmental impacts from various inputs from their corresponding industry sector averages [49,50].

Similarly, the MIET 2.0 software developed at Leiden University is a generic input–output analysis tool that enables tiered hybrid LCAs. More recent versions of commercially available software like SimaPro also enable conducting hybrid LCAs by combining process data and input–output data. The SimaPro data libraries include input–output data for a number of countries, including the United States, Japan, and Denmark [67].

Lately, some governments are encouraging the use of LCA tools in their own energy efficiency programs, such as the Australian Green Star [79], the USA Energy Star [80], the Italian Protocollo Itaca [81] or Casa Clima in Italy [82].

3.4. LCA methodological developments related to the construction industry

Despite the growing body of literature, life-cycle assessment is a relatively new concept in construction decision making and most applications found in the literature follow the traditional process based LCA approach, while a few of the studies have begun using more advanced hybrid approaches [7]. As discussed, some studies have attempted to incorporate economic considerations by including life-cycle cost analysis along with LCA. However, compared with conventional applications of LCA to standard industrial products, construction-related LCAs face additional challenges for the following reasons:

1. Site-specific impacts: Building development is a site specific process. Several local impacts may need to be considered in building assessments, such as a building's effect on the surrounding microclimate, solar access for adjacent buildings, rain and storm-water flows, and neighborhood security [83].
2. Model complexity: The amalgamation of a large number of materials and products in one building makes LCA data collection far more challenging than for most product-based applications [83]. Each of these materials and products has its own discrete life cycle and interacts as part of an assembly or system. Modelling such dynamic systems may present significant challenges [75]. In addition, construction is more than an amalgamation of materials; construction processes may have significant impacts and need to be included in the assessment framework [55]. This point is, however, not clear, since other researchers claim that the construction process can be neglected due to its low contribution to the global impact [57].
3. Scenario uncertainty: The long use phase of buildings results in considerable uncertainties in LCA findings, and analysts make assumptions for building operations and maintenance during this phase [83]. In addition, the EOL phase poses uncertainties related to renovation and remodeling or demolition and land filling of various building elements.
4. Indoor environments: Buildings imply development of indoor environments, and design choices may have a completely new set of potential impacts on occupant well-being, performance, and behavior during the use phase of the building. Typical LCA methodologies do not address such impacts even though they occur during the longest phase in the assessment and contribute the most to the total impacts [7].
5. Inclusion of recycled material data: Buildings sustainability includes the idea of using wastes and recycled materials as new building materials. Such data is usually not included in LCA databases [84].

Erlandsson and Borg [75] recognized the above challenges and concluded that building systems offer the highest complexity in LCA. They recommended not using a simple linear, static approach, beginning with construction, then operation (including maintenance), and ending with demolition and waste treatment phases. Instead, they advocated using services provided as the functional units, treating buildings as dynamic service providers that might change with modifications and rebuilding and over time, using a sequential approach in LCA, and developing a flexible LCA modeling structure that allows user choices.

The concept of dynamic LCA (DLCA) was used again in the building sector by Collinge et al. [85]. These authors define DLCA as “an approach to LCA which explicitly incorporates dynamic process modeling in the context of temporal and spatial variations in the surrounding industrial and environmental systems”. After applying the method to an institutional building, the authors conclude that the DLCA results suggest that in some cases, changes during a building lifetime can influence the LCA results more than the material and construction phases.

Huijbregts et al. [86] expressed concern regarding various uncertainties related with LCA and presented a methodology to quantify parameters, scenario, and model uncertainty simultaneously, using a residential-insulation case study. They considered uncertainties arising from variations in functional units, system boundaries, allocation methods, product life span, impact categories, and temporal and geographic heterogeneity as scenario uncertainty. Model uncertainties arise from lack of data, steady state assumptions, ignoring nonlinearities in processes, overlooking interactions among pollutants, and not taking into account the sensitivity of the receiving environment. The authors used a Monte Carlo simulation to quantify parameter uncertainty and applied various decision settings for quantification of scenario and model uncertainty. The authors suggested improvements to the proposed methodology through a more systematic analysis of scenario and model uncertainty and recommended development of LCI databases with built-in spatial and uncertainty information.

Jönsson [87] argued that conventional LCA overlooks important indoor environmental problems such as human health in building assessment. The author investigated the possibility of incorporating indoor climate issues as an impact category in LCA for building products; however, the methodological differences in LCA, material

emissions assessment (MEA), and indoor climate assessment (ICA) are determined as limiting factors to such methodological adjustments.

Hellweg et al. [88] criticized current LCA practices for not incorporating occupational health effects within the evaluation framework. They stated that "neglecting occupational health effects may result in product or process optimizations at the expense of workers′ health." The authors incorporated human health effects from workplace exposure in the LCA framework and presented three case study applications from the metal degreasing and dry cleaning industries to determine the significance of such impacts. They presented conflicting results to previous evaluations that had stressed the significance of energy use over other environmental impacts and concluded that use-phase human health effects need to be considered in environmental analysis to avoid, in their words, "burden shifting from environment to workers′ health."

Assefa et al. [89] concurred with the previous studies about the need to include occupant well-being concerns in life-cycle assessment of building performance in order to better assist decision makers. The authors used the EcoEffect methodology previously proposed by Eriksson et al. [31] and proposed evaluating final impacts resulting from both the building indoor and external environments in terms of Disability Adjusted Life Years (DALY) for human populations, which is a measure of overall disease burden, expressed as the number of years lost due to ill-health, disability or early death. DALY is also a standard metric in life-cycle inventory assessment models. In addition, they suggested conducting a parallel life-cycle cost analysis for the economic evaluation.

Abeysundra et al. [90] proposed a three-legged methodology to assess building products from the environmental, social, and economic life-cycle perspective. The authors presented an evaluation of timber and aluminum doors and windows using data from Sri Lankan buildings. They used process-based LCA to assess the environmental impacts, life-cycle costing methodology for the economic analysis, and engineer and occupant surveys to assess the social effects of both alternatives. Interestingly, they found that timber doors and windows were superior on the environmental and economic scales, whereas the aluminum solutions were found preferable on the social scale, which points to necessary trade-offs.

4. Life cycle assessment of buildings

Buildings can be categorized according to their usage i.e. residential and non-residential buildings. Residential buildings can further be divided into single-family houses and multi-family houses, and non-residential buildings are those which are used for collective use purposes, such as public buildings, transport services, tourism and sports, office, industrial, agricultural, commercial services, and stores [2].

Zabalza Bribián et al. [21] presented the main target groups for applying LCA in the early design phases of a building, showing that the main potential users of LCA are property developers, architects, and urban planners (Table 3).

4.1. LCA of residential buildings

Adalberth et al. [91] performed LCA on four multi-family buildings built in the year 1996 at Sweden. The functional unit was considered as usable floor area (m^2) and the lifetime of building was assumed to be 50 years. The main aim was to study different phases of life-cycle of all four buildings and to find out which phase has the highest environmental impact, and if there were any differences in environmental impact due to the choice of building construction and framework. The environmental impact was evaluated with an LCA tool developed at Danish Building Research Institute. In this study, the environmental impacts referred to GWP, AP (acidification potential), EP (eutrophication potential) and human toxicity. Different phases of a building considered were: manufacturing, transport, erection, occupation, renovation, demolition and removal phase. Value of energy consumption was calculated to be 6400 kW h/m^2 for 50 years. The occupation phase alone accounted for about 70–90% of total environmental impact caused by a building, so it is important to choose such constructions and installations options which have less environmental impact during its occupation phase.

Arpke and Hutzler [92] used the LCA and LCC (life-cycle cost analysis) techniques to study the use of water in multi-occupant buildings. The selected locations for this study were Boulder, Colombia; Houghton, Michigan; Ames, Iowa and Newark, New Jersey located in US. In this analysis Building for Environment and Economic sustainability (BEES) [93] tool Version 3.0 was used and it was applicable for both LCA and LCC. This tool was used to study a 25 year operational life cycle for plumbing fixtures and water-consuming appliances for four different multi-occupant buildings: an apartment, a college dormitory, a motel and an office building. The efficient fixtures and appliances should be used rather than conventional fixtures and appliances; and the use of natural gas rather than electricity for water heating should be done because $80,000 were saved if natural gas was used to heat water as an alternate for electricity.

Norman et al. [94] compared high and low populated buildings for their energy use and GHG emissions. The paper illustrates that the choice of functional unit is highly relevant for full understanding of urban density effects. Therefore two functional units were selected; living area (per m^2 basis) and number of lives in a house (per capita basis). Both conditions were selected for Toronto (Canada). The EIO-LCA (Economic input–output based LCA) was

Table 3
Application of LCA to the building sector [21].

Type of user	Stage of the process	Purpose of LCA use
Consultants advising municipalities, urban designers	Preliminary phases	Setting targets at municipal level Defining zones where residential/office building is encouraged or prohibited Setting targets for development areas
Property developers and clients	Preliminary phases	Choosing a building site Sizing a project Setting environmental targets in a programme
Architects	Early design (sketch) and detailed design in collaboration with engineers Design of a renovation project	Comparing design options (geometry/orientation, technical choices)
Engineers/consultants	Early design in collaboration with architects, and detailed design Design of a renovation project	Comparing design options (geometry, technical choices)

used to estimate the environmental impacts of material manufacturing required for construction of infrastructure. EIO-LCA is a tool developed by researchers at Carnegie Mellon University [50]. For building operations nationally averaged public datasets were utilized and detailed location-specific data for the Greater Toronto area were used for public and private transportation. Energy use and GHG emission estimates per person-kilometer for different transportation models were taken from previously submitted report by Kennedy [95]. This study showed that embodied energy and GHG emissions resulting from material production across the supply chain were approximately 1.5 times higher for low-density case study than the high-density case study on per capita basis; and the high-density development scenario became 1.25 times more energy and GHG emissions intensive than low-density if considered for unit living area basis. Also the EIO-LCA analysis performed in this study disclosed the fact that the most important construction materials contributing to embodied energy and GHGs for both density cases were brick, windows, drywall and structural concrete used in the buildings. These four materials in combined accounted for 60–70% of the total embodied energy and production related GHG impacts for both low and high-density case studies.

Guggemos and Horvath [96] compared environmental effects of steel and concrete framed buildings using LCA. Two five-storey buildings with floor area of 4400 m^2 were considered which were located in the Midwestern US and were expected to be used for 50 years. In this study two methods, process based LCA and EIO-LCA, were used to evaluate life-cycle environmental effects of each building through different phases: material manufacturing, construction, use, maintenance and demolition phase. The results showed that concrete structural-frame had more associate energy use and emissions due to longer installation process.

Blengini [97] performed LCA of building which was demolished in the year 2004 by controlled blasting. The adopted functional unit used in the current case-study was 1 m^2 net floor area, over a period of 1 year. This residential building was situated at Turin (Italy). In this study demolition phase and its recycling potential were studied. The life cycle impact assessment (LCIA) phase was initially focused on the characterization and six energy and environmental indicators were considered, GER (gross energy requirement), GWP, ODP (ozone depletion potential), AP, EP and POCP (photochemical ozone creation potential). SimaPro 6.0 [67] and Boustead Model 5 [98] were used as supporting tools in order to implement the LCA model and carried out the results. The results demonstrated that building waste recycling is not only economically feasible and profitable but also sustainable from the energetic and environmental point of view.

From most of the available literature, one can conclude that the operational phase contributes more than 80–85% share in the total life cycle energy of buildings [2,10,99,100]. Therefore, future efforts should be focused on reducing the operational phase, even at some cost to other less significant phases.

4.2. LCA of non-residential buildings

Junnila and Horvath [101] studied the significant environmental aspects of a new high-end office building with a life span of over 50 years. In this study functional unit is considered as 1 kW h/m^2/year and location of study was at Southern Finland (Northern Europe). The LCA performed here had three main phases – inventory analysis for quantifying emissions and wastes, impact assessment for evaluating the potential environmental impacts from the inventory of emissions and wastes, and interpretation for defining the most significant aspects. In this study life cycle of a building was divided into five main phases; building materials manufacturing, construction process, use of the building, maintenance, and demolition. The result shows that the most of the impacts are associated with electricity use and building materials manufacturing. Particularly, electricity used in lighting, HVAC systems, heat conduction through the structures, manufacturing maintenance of steel, concrete and paint, and office waste management were identified as the most significant aspects. GHG emissions were estimated to be 48,000 t CO_2eq/m^2 per 50 years.

Kofoworola and Gheewala [102] conducted an LCA of an office building in Thailand and found that steel and concrete accounted for most of the material-related environmental impacts, and use-phase energy consumption accounted for 52% of total life-cycle impacts.

Richman et al. [100] performed LCA for cold storage buildings in North America. They considered RSI value (RSI=insulating value) as a functional unit, as energy loss is proportional to 1/RSI. The models were simulated as if they were located in the cities of Tamp, Florida and Milwaukee, Wisconsin (US). This research basically examined the estimated average roof insulation requirement in modern cold storage buildings. Both environmental and economic aspects were considered. This study shows that there is a need to improve the level of insulation; depending upon the climatic conditions i.e. RSI-8.45 to RSI-9.86 insulation should be used in cold climates and RSI-9.86 to RSI-11.27 insulation should be used in warm climates.

Scheuer et al. [103] performed LCA on a 7300 m^2 six-storey building whose projected life was 75 years at SWH (Sam Wyly Hall). The building is located on the University of Michigan Campus, Ann Arbor, Michigan, US. LCA was done in accordance with EPA (Environmental Protection Agency), SETAC (Society for Environmental Toxicity and Chemistry), and ISO standards for LCA [104–106]. Most of the data was taken from the DEAMTM database [77] and other material production data was taken from two databases by Swiss Agency for the Environment, Forests and Landscape [107], SimaPro software [67] and from Franklin Associates Reports [108]. Primary energy consumption, GWP, ODP, NP (nitrification potential), AP, and solid waste generation were the impact categories considered in the life cycle environmental impacts from SWH. Computer modeling was done in order to determine the primary energy consumption for heating, cooling, ventilation, lighting and water consumption. The primary energy intensity over the buildings life cycle was calculated to be 316 GJ/m^2. HVAC and electricity alone accounted for 94.4% of life cycle primary energy consumption. An inventory analysis of three different phases was done: Material placement, Operations and Demolition phase. Results showed that the optimization of operations phase performance should be primary emphasis for design, as in all measures, operations phase alone accounted for more than 83% of total environmental burdens.

Kofoworola and Gheewala [109] operated an LCA for an office building in Thailand. The building used in this study is a 38 storey building in the central business district of Bangkok and its service life was estimated to be 50 years. The functional unit for this study was considered as 60,000 m^2 gross floor area of building. This study covered whole life cycle including material production, consumption, construction, occupation, maintenance, demolition and disposal. Inventory data was simulated in an LCA model and environmental impacts for each phase were computed. Main three impact categories considered were; GWP, AP and photo-oxidant potential. Two LCA methodologies were used in the study, i.e. a process-based LCA and the EIO-LCA [110–115]. The results showed that steel and concrete were the most significant materials, both in terms of quantities used and also for their associate environmental impacts at the manufacturing stage. Also the life cycle environmental impacts of commercial buildings were dominated by the operation stage, which accounts 52% of total global warming, 66% of total acidification and 71% of total photo-oxidant formation potential, respectively.

Arena and Rosa [116] considered a school building and performed an LCA to compare different building technologies which have been applied in a rural school building for obtaining thermal comfort with minimum fossil energy consumption. This school building is situated in Lavalle, a small town in Northern Mendoza (Argentina). Life span of building was considered to be 50 years. A simplified LCA methodology was used and only construction and operational phases were considered. Environmental impacts which were considered in this study are; GWP, EP, ARP (Acid Rain Potential), PSP (Photo-Smog Potential), resource consumption and TP (Toxicity Potential). For all calculations regarding inventory, impact assessment and normalization phases the SBID (Society of British Interior Design) database was used [117]. The annual energy savings and global energy savings (for 50 years) were calculated and showed that the annual energy savings during use phase were 5307.5 MJ/year, and global energy savings for 50 years life span were 265,374.5 MJ/year. This study showed that almost all the environmental aspects investigated were improved when conservative technologies were implemented. In this study, conservative technologies are those applied to a building with double brick layer walls with thermal insulation in between and a horizontal concrete roof with metal sloping.

4.3. LCA of civil engineering constructions

Moreover of the application of LCA to the buildings, LCA have been used in civil engineering projects as well [5]. For example, regarding highway constructions, Birgisdóttir et al. [118] compared two scenarios with natural vs. different types of materials. The method of the LCA was evaluated in ROAD-RES tool, which can be used for LCA in the road construction and waste disposal. Environmental impacts like global warming, acidification and ecotoxicity were analyzed. The assessment showed that the difference between the scenarios was marginal in terms of environmental impacts and resource consumption. The majority of the environmental impacts were related to emissions from combustion of fossil fuels. Potential pollution of groundwater due to leaching of salts appeared to be important potential resource consumption, primarily due to road salting.

Mroueh et al. [119] carried out a similar study of these impacts. Both investigations show that the application of LCA pursue strategies to minimize the environmental loads, resource consumption and applied strategies such as recycling and reusing of building materials. The results of case studies indicate that the production and transport of the materials used in road constructions produce the most significant environmental burdens. Production of the bitumen and cement, crushing of materials and transport of materials are the most energy consuming single life-cycle stages of the construction. A large part of the emissions to atmosphere originates from energy production. In the expert assessment, consumption of natural materials and leaching behavior were also regarded as being of great significance.

Within this category one can also include pavements; although not a part of a building per se, pavements are an important part of urban areas, where buildings are included. Santero et al. [120] published a very complete review of LCA of pavements.

According to Santero et al. [120], the environmental impacts from pavements are best characterized using a life-cycle assessment (LCA) approach. When LCA is coupled with life-cycle cost analysis (LCCA), decision-makers are able to better ascertain the total impacts of a proposed project or policy. LCCA is already widely adopted in departments of transportation, with bulk of U.S. states employing at least some form of LCCA Ozbay et al.[121]. Adding LCA to their toolbox will increase the ability of decision-makers to reach economic and environmental goals.

Vidal et al. [122] carried out a comprehensive LCA of asphalt pavements including hot mix asphalt, warm mix asphalt with the addition of synthetic zeolites, and asphalt mixes with reclaimed asphalt pavement. The environmental impacts associated with energy consumption, air emissions, and other environmental impacts resulting from all other steps of the pavement process were assessed. All endpoint impacts as well as climate change, fossil depletion and total cumulative energy demand were decreased by 13–14% by adding 15% reclaimed asphalt pavement. A key advantage of warm mix asphalt is the potentially greater use of reclaimed asphalt pavement. Thus, the decrease in the impacts achieved by adding large amounts of reclaimed asphalt pavement to warm mix asphalt could turn these asphalt mixes into a good alternative to hot mix asphalt in environmental terms.

5. Life cycle energy analysis of buildings

The total life cycle energy of a building includes both embodied energy and operating energy [120,121,123]:

(1) Embodied energy (EE): sequestered in building materials during all processes of production, on-site construction, and final demolition and disposal.
(2) Operating energy (OE): expended in maintaining the inside environment through processes such as heating and cooling, lighting and operating appliances.

Until recently, only operating energy was considered, owing to its larger share in the total life cycle energy. However, due to the advent of energy efficient equipment and appliances, along with more advanced and effective insulation materials, the potential for curbing operating energy has increased and as a result, the current emphasis has shifted to include embodied energy in building materials [124–127]. Ding [124] suggests that the production of building components off-site accounts for 75% of the total energy embedded in buildings [128] and this share of energy is gradually increasing as a result of the increased use of high energy intensive materials [4,129]. Thus, there is a genuine demand to calibrate the performance of buildings in terms of both embodied and operating energy in order to reduce energy consumption [129,130]. At a macro-level, proper accountability of embodied and operating energies will contribute to data and information needed to create an energy economy that accounts for indirect and direct contributions.

Langston and Langston [129] suggest that, while measuring operating energy is easy and less complicated, determining embodied energy is more complex and time consuming. Furthermore, there is currently no generally accepted method available to compute embodied energy accurately and consistently [124,131] and as a result, wide variations in measurement figures are inevitable, owing to various factors [124,125,129,131,132].

Treloar et al. [130] presented an evaluation of the embodied energy content of several commonly used construction materials, using a case study in Australia. The authors argued that embodied energy deserves attention along with the building operational energy from a life-cycle perspective. The results were presented as the building′s embodied energy content from the materials as well as from various building elements (e.g., roof, services, etc.).

5.1. Life cycle energy analysis in the literature

Buildings consume energy directly or indirectly in all phases of their life cycle right from the cradle to the grave and there is interplay between phases of energy use (embodied and operating energy). Hence, they need to be analyzed from life cycle point of view. Bekker [133] highlighted that in the building sector a life

cycle approach is an appropriate method for analysis of energy and use of other natural resources as well as the impact on the environment. This effort was done by Ramesh et al. [4].

Later on Adalberth [134] presented a method describing the calculation of the energy use during the life cycle of a building. The method is applied to gain insight into the total energy use of dwellings in its life cycle in a previous paper Adalberth [135]. The paper presented case studies of the total energy use for three single-unit dwellings built in Sweden wherein, it was reported that 85% of the total energy usage was required during the operation phase and energy used in manufacturing all the construction materials employed in construction with the erection and renovation amounts approximately to 15% of the total energy use. The transportation and process energy used during erection and demolition of the dwellings comprises approximately 1% of the total energy requirement. Several other similar studies are reported in the open literature for residential buildings [46,136–138] and office buildings [109,139,140].

Table 4 shows an abstract of data sources adopted by different authors to evaluate life cycle energy analysis of buildings.

From the case studies presented in Adalberth [134] it is concluded that in life cycle energy analysis, operating energy has a major share (80–90%), followed by embodied energy (10–20%), whereas demolition and other process energy has negligible or little share. Since operating energy of the buildings has largest share in life cycle energy distribution, reducing it appears to be the most important aspect for the design of buildings which demand less energy throughout their life cycle. In order to reduce operational energy demand of the buildings, passive and active measures such as providing higher insulation on external walls and roof, using gas filled multiple pane windows with low emissivity (LE) coatings, ventilation air heat recovery from exhaust air, heat pumps coupled with air or ground/water heat sources, solar thermal collectors and building integrated solar photovoltaic panels, green roofs and green facades, etc. were examined in life cycle perspective by many researchers. Mithraratne and Vale [141] recommended provision of higher insulation to a timber framed house situated in New Zealand as an energy saving strategy. Different versions of the same building with varying active and passive measures were also analyzed [91,142]. It is observed that reductions in life cycle energy of the buildings over their conventional ones are proportional to the degree and number of energy saving measures used in the building. Conventional building refers to a building built according to the common practice of a specific country. However, reduced demand for operating and life cycle energy is achieved by a little increase in embodied energy of the building due to the energy intensive materials used in technical and other installations. Thormark [143] reported that embodied energy and its share in the life cycle energy for low energy building is higher than conventional ones.

Though embodied energy constitutes only 10–20% to life cycle energy, opportunity for its reduction should not be ignored. There is a potential for reducing embodied energy requirements through use of materials in the construction that requires less energy during manufacturing [144]. While using low energy materials, attention must be focused on their thermal properties and longevity as they have impact on energy use in other phases of a building′s life cycle. Oka et al. [145] quantified energy consumption and environmental pollution caused by construction in Japan. Buchanan and Honey [146] made a detailed study on embodied energy of buildings and resulting carbon dioxide emissions with wood, concrete, and steel structures for office and residential purposes in New Zealand and concluded that wood constructions have less embodied energy than concrete and steel structures. Venkatarama Reddy and Jagadish [147] estimated the embodied energy of residential buildings using different construction techniques and low energy materials and obtained 30–45% reduction in embodied energy. Shukla et al. [148] evaluated embodied energy of an adobe house in Indian context. The house was constructed using low energy intensive materials like soil, sand, cow dung, etc. For the adobe house [148], about 50% reduction in embodied energy was observed compared to a conventional concrete house. This reduction was achieved due to the use of low energy intensive and locally available materials (e.g. soil, sand, cow dung, etc.) compared to burnt clay bricks, concrete, cement, etc., in the concrete house. Another opportunity for reducing embodied energy is through use of recycling materials in the construction. Thormark [149] studied two cases: (i) the building which was built with a large proportion of reused materials and components; (ii) the building in which all materials and components had been new. The results showed that about 55% of energy could be saved with reused materials and components.

Table 4
Data sources for life cycle energy analysis [10].

Life cycle phase	Activity	Possible sources of data
(a) Manufacturing phase	Building material production	Manufacturing energy data of the building materials from literature, economic input and output tables, process analysis, hybrid analysis Quantities estimated from building drawings, bill of materials and from interviews with building designer, contractor/owner
	Transport	Average distances for material transport Energy data for transport operations
	Building construction including refurbishment	Energy use from site visit
(b) Use phase	Use of electricity and fuels for heating, sanitary water and lighting	Simulation software – ENERGY-PLUS, VISUAL DOE, E-QUEST, DESIGN BUILDER, ENORM, TRNSYS, ECOTECT, SUNCODE, etc., annual electricity bills, household survey on energy use Inventory data for fuel production Electricity mix data
(c) Demolition phase	Building demolition	Demolition operations and quantities from specific measured data Use of equipment and explosives from data base
	Transport	Average distances for material transport Energy data for transport operations
	Recycling	Specific measurement data
(d) Life cycle energy	Total energy use of the building in its life cycle	Phase a+b+c
(e) Life cycle assessment	Life cycle material and energy flow estimation	Phase a+b+c
	Impact assessment that building makes on the environment	Greenhouse effect or global warming, ozone depletion, acidification, eutrophication, photochemical smog, etc. estimated using software—SIMAPRO, ECOBAT, LEGEP, BEES, ATHENA, etc

In order to directly address a set of specific environmental loads caused by buildings and their operation, researchers have increased the scope of analysis beyond pure energy accounting and applied a full life cycle assessment analysis in their studies [91,102,150,151]. Environmental impacts like global warming potential, acidification potential, and photo-oxidant formation potential are considered in these studies. Seo and Hwang [152] examined and estimated CO_2 emissions in the entire life cycle of buildings.

From these studies, it may be observed that the impact of different phases of the building on environment is similar to energy share of these phases in the life cycle energy of the buildings [10]. LCA is much dependent on the primary sources of the energy of a particular place and conversion efficiency of materials production processes. If energy source is changed from fossil to renewable, environmental impact drastically changes. Also, it can be seen that the renewable sources of energy have less impact on the environment.

There are also comparative life cycle energy assessment studies in the open literature; Marceau and VanGeem [153] presented life cycle energy assessment of a single-family house modeled with two types of exterior walls: wood framed and insulating concrete form (ICF). The house was modeled in five cities of different climates in US. The results showed that in almost all cases, for a given climate, the impact indicators are greater for the wood house than for the ICF house. Xing et al. [154] presented the life cycle assessment of office buildings constructed in China using steel and concrete. They showed that life cycle energy consumption of steel was 75.1% that of concrete and that the environmental emission was less than a half, therefore, on the life cycle energy consumption and environmental emissions of the building materials, steel-framed buildings is superior to the concrete-framed one.

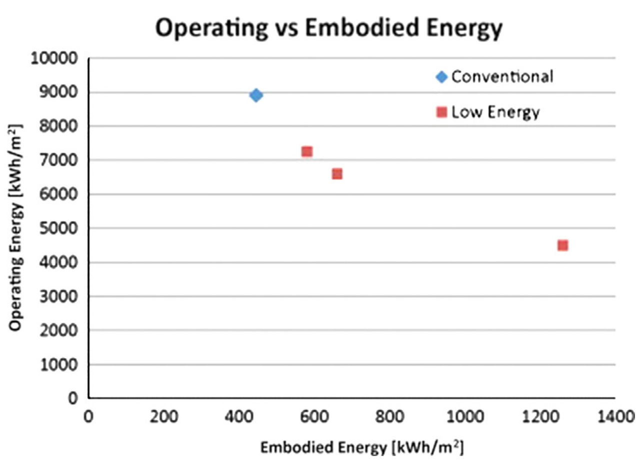

Fig. 3. Interplay between operating and embodied energy for case studies [10,142].

Scheuer et al. [103] carried a study on a six storey university building in Michigan, USA. Building life span of 75 years was used for the study. It was noted that the materials are responsible for 94% of the life cycle embodied energy (excluding construction and transportation). However, these materials only account for 74% of the total building mass. The largest contributors to embodied energy are steel, cement and sand. These are high due to their large mass and not necessarily their material production energy. Aluminum, mostly used for window frames is also significant primarily because of its energy intensity. If all other parameters are kept constant replacing conventional building material by low carbon emitting material improves environmental performance significantly.

Kua and Wong [155] analyzed a six-story ramped up food-factory in Singapore. In this study, the authors carried out a whole-building LCEA and life cycle GHG analysis (LCGA) extending the traditional system boundary drawn for a whole-building LCA to include the management of wastes produced during building operations. It was found that waste management produces much more emissions than the operation stage.

5.2. Low energy buildings

Low energy buildings are the buildings having specific design that demand less operating and life cycle energy than if built according to conventional criteria with parity of all other conditions [4]. Design of low energy building is achieved by reducing its operating energy through active and passive technologies. But, reduction in operating energy is generally accompanied by little increase in embodied energy of the building due to energy intensive materials used in the energy saving measures (Fig. 3).

Table 5 shows the life cycle energy savings through operating energy reduction by installing passive and active measures for the case studies mentioned in Adalberth [91], Citherlet and Defaux [45], and Winther and Hestnes [142]. It shows that life cycle energy savings are in accordance with reduction in operating energy which in turn is proportional to the degree and number of passive and active energy saving measures used in the building. This indicates that one can go on reducing energy use for operation of the building in order to produce low energy buildings by increased use of passive and active energy saving measures and at one stage operating energy can be made zero and thus produce zero energy buildings (self-sufficient) [156]. A zero energy building requires neither fuels nor electricity for its operation as all the energy it

Table 5
Energy savings with active and passive measures over conventional constructions [10].

Energy saving measures (passive and active)	Reduction in operating energy (%)	Life cycle energy savings (%)
Conventional	–	–
Ventilation: mechanical supply and exhaust system with plate heat exchanger to recover heat	15	14
Ventilation: mechanical supply and exhaust system with plate heat exchanger and windows; single pane and a sealed argon filled unit with low emission coatings	–	18
Conventional	–	–
Exhaust air heat pump preheat ventilation air and hot water	21	19
Solar collectors preheat hot water and air heat recovery unit efficiency 70%	30	26
Ground coil and heat pump system for space and water heating, PV system and air heat recovery unit efficiency 85%	62	50
Conventional	–	–
Increased insulation on façades, roof and slab, heat pump coupled to ground, 55% heat recovery from exhaust air	20	16
Super insulation on façade, roof and slab, 3 panel windows with two low e-coatings, heat pump coupled to ground, 55% heat recovery from exhaust air, solar thermal collectors for hot water, PV panels to generate half of the electricity required	54	49

needs is locally produced (utilizing solar and wind sources) and stored.

Sartori and Hestnes [4] reviewed life cycle energy consumption of conventional, low energy and zero energy buildings. Six versions of the building (one conventional, four low energy, and one self-sufficient) are analyzed in the German context. Results show that life cycle energy of the self-sufficient building is higher than some of its low energy versions (Fig. 4). This is due to the fact that, in case of low energy buildings, increase in embodied energy because of energy saving measures is little compared to decrease in its operating energy; hence, their life cycle energy comes down significantly. But, in case of self-sufficient house, though its operating energy is zero, its embodied energy is so high that it exceeded life cycle energy of some of the low energy cases. This indicates that self-sufficient house is not the lowest life cycle energy consumer among all versions of a building and there is a limit for life cycle energy savings through reduction in operating energy by installing complex and energy intensive technical installations.

Similarly, Winther and Hestnes [142] compared self-sufficient house in Freiburg with energy use of the five versions of the row houses at Hamar. Embodied energy of self-sufficient house was larger than highest energy user of five versions. The authors expressed a view that there is a limit to reduction in energy use for operation by energy intensive domestic engineering systems. But these studies did not determine the maximum energy reduction for operation before the embodied energy compensates it from a life cycle point of view. This limit varies from one study to another and will not be unique even for particular studies as it depends on the type and mix of active and passive measures used, climatic conditions of the place, and materials used in the construction. This requires more detailed study. But, conclusion that can be drawn at this stage is that, carefully designed low energy buildings perform better than self-sufficient houses in life cycle context. Too many technical installations in order to make building self-sufficient are not desirable [10].

Energy efficient building are designed to minimize heating, cooling and lighting energy loads, so that attention is now paid on the energy consumption related to inhabitants (e.g. use of appliances) and life cycle issues: fabrication of materials, construction, maintenance, dismantling and waste treatment. In order to take into consideration occupants behavior, Peuportier et al., [157] developed an approach based in carrying out a sensitivity study of thermal simulation linked with LCA. They applied the method to a case study of two attached passive houses built in France. They concluded that the environmental benefit of higher quality constructions, but also how occupants behavior strongly influences the environmental performance of these buildings. Despite this strong influence, different occupants behaviors did not modify the ranking between standard and passive designs so that these LCA results can be considered robust in this aspect. Nevertheless, authors recognize that the method needs to be applied to more case studies to validate these conclusions.

Proietti et al. [158] completed an LCA in order to investigate the environmental impact of a passive house including a mix of advanced technological solutions in the building envelope, recycled materials, reuse of the rainwater, reduced energy consumption, renewable energy utilization, and intelligent use of the insulation. The results showed that applying energy saving measures (highly insulated building envelope and passive-house standard, solar PV, waste recycling and recycled products in pre-production phase) could significantly decrease the impact of modern dwellings, with the consciousness that new ways of building do not always provide a positive environmental outcome. A similar study was carried out by Thiel et al. [159] in USA and by Monahan and Powell [160], although this last study emphasizes again the embodied energy concept.

5.3. Life cycle energy analysis by construction type

Embodied energy content varies greatly with different construction types. Different studies based on the types of framework structures of buildings, show these variations in life cycle energy as well as embodied energy [161–164].

Fig. 5 shows the embodied energy and the life cycle energy of three forms of construction for multi-residential buildings in Melbourne (an eight-storey, 3943 m^2 multi-residential building): conventional concrete construction, modular prefabricated steel, and modular prefabricated timber [162].

Gong et al. [163] show on three types of residential buildings with framework structures in Beijing—concrete framework construction (CFC), light-gauge steel framework construction (SFC), and wood framework construction (WFC)—that over the life cycle, the energy consumption of CFC is almost the same as that of SFC, and each of them is approximately 30% higher than that of WFC. The net CO_2 emission of CFC is 44% higher than that of SFC and 49% higher than that of WFC. The net CO_2 emissions in the transport category cannot be ignored, with proportions amounting to 8%, 12%, and 11% for WFC, SFC, and CFC, respectively.

Gustavsson and Joelsson [164] show that for a conventional and a low-energy building the primary energy use for production can be up to 45% and 60%, respectively, of the total, depending on the energy supply system, and with larger variations for conventional buildings. The primary energy used and the CO_2 emission resulting from production are lower for wood-framed constructions than for concrete-framed constructions (Fig. 6).

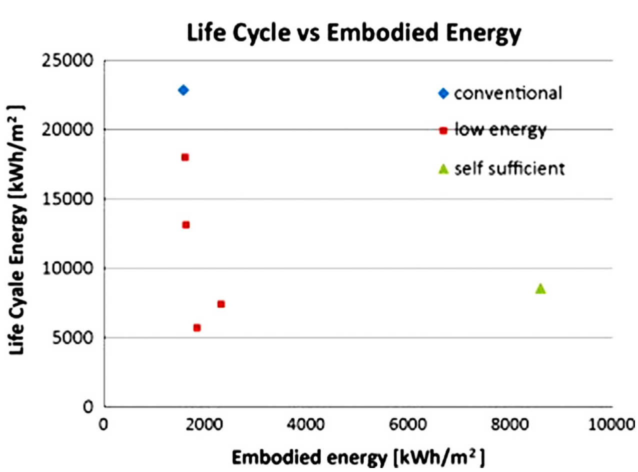

Fig. 4. Life cycle vs. embodied energy for case studies reviewed [4,10].

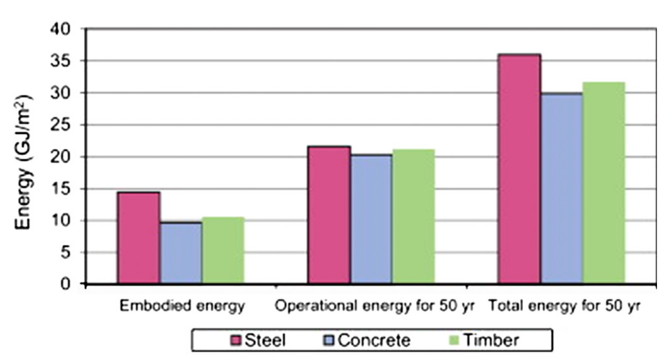

Fig. 5. Life cycle energy requirements of three construction types over 50 years [162].

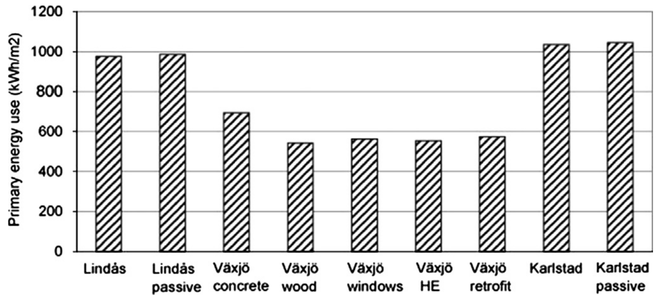

Fig. 6. Primary energy use for the production of conventional and low-energy residential buildings [164].

Finally, Huberman and Pearlmutter [161] found out that the cumulative energy saved over a 50-year life cycle by this material substitution is on the order of 20%.

6. Life cycle cost analysis of buildings

Compared to other products, buildings are more difficult to evaluate for the following reasons: they are large in scale, complex in materials and function and temporally dynamic due to limited service life of building components and changing user requirements [9]. Moreover, their production processes are much less standardized than most manufactured goods because of the unique character of each building.

There is limited quantitative information about the environmental impacts of the production and manufacturing of construction materials, or the actual process of construction and demolition, making environmental assessments of the building industry challenging [103]. One attempt was carried out by Mezher and Chedid [165] who studied the allocation of energy resources amongst end uses and developed a method for optimizing six objective functions (minimization of cost, maximization of system efficiency, minimization of use of conventional fossil fuel, maximizing use of locally available material, maximizing employment, and minimizing CO_2, SO_2 emissions).

Substitution between energy and CO_2 intensive materials is a potentially important climate mitigation strategy. Nässén et al. [166] compare buildings with concrete frames and wooden frames concerning their life-time carbon dioxide emissions as well as their total material, energy and carbon dioxide costs (Fig. 7). The net present costs for the different buildings are also affected by the future energy supply system, even though the impact is small, especially compared to the total construction cost. Concluding that it is unclear whether wood framed buildings will be a cost-effective carbon mitigation option and that further analyses of costs should be performed before prescriptive materials policies are enforced in the buildings sector.

7. Summary and conclusions

LCA has been used for environmental evaluation of buildings and building related industry and sector (including construction products, construction systems, buildings, and civil engineering constructions) through a very scattered literature, which is summarized and organized here. More recently, LCEA and LCCA are starting to be used also for similar purposes.

The review, agreeing with previous ones [8], shows that the case studies found in the literature are difficult to compare because of their specific properties like building type, climate, comfort requirements, local regulations, etc. A comparison can be seen in Table 6, where most case studies considered in this review

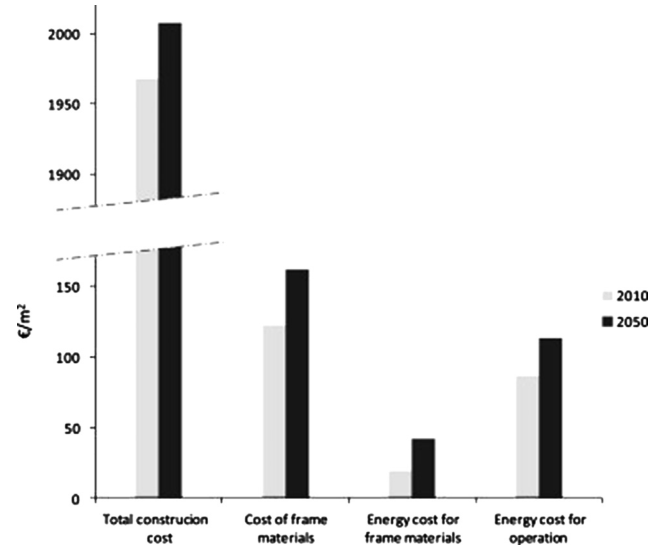

Fig. 7. Comparison of different costs in a buildings life cycle [165]. The energy cost of frame materials is a sub-set of the cost of frame materials which in turn is a sub-set of the total construction cost. All costs are taken from the renewable scenario and represent the average of the wood and concrete frames. The energy cost for heating during 100 years of operation is calculated with a discount rate of 5%.

are listed. The most important phases of LCA are compared, that is the scope, the lifetime, the functional unit considered, the system boundaries, the location, and the building typology.

When the scope is revised, it is clear that this is the main difference between all the studies, here one can already see when the LCA is focused in the materials of the building or when the focus is the whole building.

The lifetime considered is presented in most of the papers, but here two considerations can be done. The first one is that only a few studies carry out a parametric study considering different lifetime of the buildings, to see if this influences the results of the LCA or LCEA. On the other hand, one can compare the lifetime considered by most authors, considering between 10 and 100-year, with 50% of the papers consider 50-years, 19% consider 40-years and 9% consider 80 or 100-years.

The functional unit is not mentioned in all studies; usually those considering the LCA or LCEA of whole buildings do not identify it. Important to mention that there is absolutely no agreement on the functional unit to be considered, one more reason to make more difficult comparison between studies.

On the other hand, the system boundaries are usually clearly identified, and depend a lot on the scope of the study. The papers which consider whole buildings usually also consider the whole LCA phases (production, use and demolition); but those considering materials either consider wider boundaries to include all phase of the materials production, or consider only the manufacturing phase of the LCA.

Finally, most if not all studies clearly identify the building typology considered and its location, since usually all studies are based on real buildings.

After considering all the studies presented here, it is clear that most of them are carried out in developed countries (Fig. 8). There are no cases from Africa, while only one from South America was found. Asia and Oceania is a little bit better represented, since several papers can be found from India, China, Japan, Australia, Malaysia, and others were found. On the other hand, a lot of cases from North America and Europe were available.

Fig. 8 also shows that most of the literature found from America is LCA of the building industry or of buildings, while in Asia and Oceania most cases are LCEA. Europe presents similar amount of

Table 6
Case studies of LCA, LCEA and LCC of buildings and building sector.

Section paper	Reference	Scope	Lifetime of the analysis	Functional unit	System boundaries	Location	Building typology
3. LCA in the building industry	Asdrubali et al. [9]	Concrete structure, bricks envelope with thermal insulation, aluminum windows, gas-fired heating system	50-Years	A detached residential house, aPer multi-family and a multi-story office building	Complete LCA	Perugia, Italy	A detached residential house, aPer multi-family and a multi-story office building
	Jönsson et al. [25]	Floor coverings: linoleum, vinyl flooring and solid wood flooring	25, 20 and 40 Years	One square meter of flooring during one year of operation	Production, resource use, energy use, emissions to air and water, and waste generation.	Sweden	–
	Asif et al. [26]	Materials used in residential construction: wood, aluminum, glass, concrete and ceramic tiles	–	–	Not clear	Scotland, UK	3-bed room semi-detached house
	Ximenes and Grant [27]	To determine the greenhouse outcomes of life cycle of wood products in comparison with alternative building materials	50-Years	The supply of base building elements for domestic houses	Extraction, manufacture, transport, use in construction, maintenance and disposal	Sydney, Australia	Timber wood (Affinity house) and "timber-maximised" alternative (Villina house)
	Koroneos and Dompros [28]	Brick production process	80-Years	One tone of a specific type of brick	Raw material acquisition, industrial production, packaging and transportation	Industrial area of Sindos, Thessaloniki, Greece	No building
	Wu et al. [29]	Various types of cement and steel	–	–	Impact analysis step of the LCA	Beijing, China	No building
	Esin [30]	Several building materials	–	–	Production process	Gebze and its vicinity, Marmara region, Turkey	No building
	Nebel et al. [26]	Wood floor coverings	50-Years home, 10, 20, 25, 50-years for cover-ings	1 m² of laid wood floor covering assuming average wear and tear in a home that is completely refurbished after 50 years	Manufacturing of glues and varnishes, manufacturing of auxiliaries (e.g. lubricants), provision of energy (e.g. electricity, diesel), maintenance of machinery	Germany	No building
	Nicoletti et al. [27]	Floor materials: ceramic and marble tiles	40-Years	1 m^2 of flooring tile	The entire life cycle of the two systems	Italy	No building
	van der Lugt et al. [28]	Bamboo, compared to steel and timber wood	–	Column, beam and rail, as used in the pedestrian bridge in the "Cherry blossom garden" in the Amsterdam Woods, each element with its original technical requirements	Production process and life span	Switzerland, Netherlands, Germany	No building
	Babaizadeh and Hassan [35]	Nano-sized titanium dioxide coating	40-Years	One squared meter of titanium dioxide coated glass	Glass coating system boundaries	Baton Rouge, Louisiana, USA	Residential building
	van den Heede and de Belie [36]	Comparison between traditional and "green" concretes	–	Review of literature	Review of literature	–	No building
	de Gracia et al. [37]	Phase change materials (PCM), paraffin and salt hydrate	50, 75, 100-Years	–	Manufacturing/ dismantling and operation phases	Puigverd de Lleida, Spain	Experimental brick cubicles
	Castell et al. [38]	Phase change materials (PCM), paraffin and salt hydrate	50, 75, 100-Years	–	Manufacturing/ dismantling and operation phases	Puigverd de Lleida, Spain	Experimental alveolar brick cubicles
	Rincón et al. [39]	To evaluate the environmental impacts of different constructive systems of the building envelope (with and w/o PCM), by MFA and LCA	80-Years	–	Manufacturing, operational and disposal phases	Puigverd de Lleida, Spain	Experimental brick and alveolar brick cubicles
	Menoufi et al. [40]	Phase change materials (PCM), paraffin, salt hydrates and ester	–	–	Manufacturing and disposal phase	Puigverd de Lleida, Spain	Experimental brick cubicles
	Menoufi et al. [41]	Phase change materials (PCM), paraffin and salt hydrate	25, 50–100-Years	–	Manufacturing and disposal phase	Puigverd de Lleida, Spain	Experimental concrete, brick and alveolar brick cubicles
	Aranda-Usón [42]	Phase change material addition in tiles	50-Years	Commercial offices with only one floor	Use phase and PCM disposal/recycling	Spain (Almeria,	Tiles building

Table 6 (*continued*)

Section paper	Reference	Scope	Lifetime of the analysis	Functional unit	System boundaries	Location	Building typology
						Valencia, Santander, Zaragoza, and Burgos)	
	Citherlet and Defaux 2007 [45]	Family house variants comparison	–	Building	Manufacture, transport, maintenance, deconstruction and elimination of building materials	Lausanne, Geneva lake, Switzerland	Family house: standard in force in Switzerland, requirements of a quality control label for houses with low energy consumption. a very low energy consumption building.
	Keoleian et al. [51]	Single-family house (standard home in USA)	50-Years	Building	Pre-use (materials production and construction), use (including maintenance and improvement), and demolition phases	Ann Arbor, Michigan, USA	Standard US single-family house
	Radhi and Sharples [54]	To assess the impact of different facade parameters on global warming	60-Years	The "external heat gain", be represented by electricity consumed by the HVAC system	Extraction, manufacturing and assembly of materials, transport, construction, maintenance and deconstruction	Bahrain	Two-stories house: different facade materials
	Kellenberger and Althaus [57]	Building components: e. g. wooden wall, concrete roof	80-Years	1 m^2 of opaque building component with similar heat transfer rate over 80 years	All-inclusive building components: production, transport, construction of building component, operation of building, disposal	Switzerland	No building
	Vieira and Horvath [59]	Concrete used in a typical US office building	–	–	End-life of buildings	USA	Typical US office building
	Collinge et al. [85]	To establish a dynamic LCA (DLCA) approach and test this approach with a case study of an existing institutional building	75-Years	Institutional building over its assumed lifetime	Primarily materials for construction and renovation and electricity/fuels for building operation	Pittsburgh, Pennsylvania, USA	Benedum Hall at the University of Pittsburgh
4. LCA of buildings	Norman et al. [94]	Compared high and low populated buildings for their energy use and GHG emissions	50-Years	Living area (per m^2 basis) and number of lives in a house (per capita basis)	Three major elements of urban development: 1. all activities throughout the economy associated with resource extraction through material production for infrastructure; 2.the operational requirements for dwellings; and 3. the operational requirements of vehicles for personal transportation and public transit	Toronto, Canada	Office building and single-family dweling
	Kennedy [95]	Different transportation models	50-years	passenger-kms	Economic, environmental and social perspectives	Greater Toronto area, Canada	No building
	Blegini [97]	Contrasting the impact of the demolition phase	40-Years	1 m^2 net floor area, over a period of 1 year	All life cycle phases, with emphasis on production of construction materials and end-of-life management	Via Fratelli Garrone, Turin, Italy	Residential block of flats
	Shu-hua et al. [99]	Life-cycle phases energy consumption	50-Years	–	All life cycle	China	Urban residential buildings
	Kofoworola and Gheewala [101]	Commercial office building	50-Years	60,000 m^2 gross floor area of building	The entire life cycle of the office building, including manufacturing of building materials, construction, operation, maintenance, and demolition	Thailand	Commercial office building
	Scheuer et al. [103]	To examine differences that might arise between results from a "complete" inventory LCA of a building, and the results from partial LCAs or LCAs	75-year	–	All phases of life cycle	University of Michigan, Ann Arbor, Michigan, USA	University six-story building

Table 6 (*continued*)

Section paper	Reference	Scope	Lifetime of the analysis	Functional unit	System boundaries	Location	Building typology
		built on a general building model					
	Kofoworola and Gheewala [109]	To determine the embodied energy coefficients of key building materials utilized in Thailand; to assess the LCE consumption of a typical office building; to study the relative importance of the different life cycle phases and; to provide information which may be used as a basis for more effective regulation of building energy efficiency policies in Thailand	50-Year	60,000 m^2 gross floor area of building	All phases of life cycle	Central business district of Bangkok, Thailand	38-story typical office building
	Facanha and Horvath [112]	A life-cycle inventory of air emissions (CO_2, NO_x, PM10, and CO) associate with the transportation of goods by road, rail, and air in the U.S.	10-Years	Ton-mile	Manufacturing, use, maintenance, and end-of-life (EOL) of vehicles, the construction, operation, maintenance, and EOL of transportation infrastructure, as well as oil exploration, fuel refining, and fuel distribution	Continental USA	No building
	Arena and Rosa [116]	To perform a comparison of traditional and energy-conservative technologies applied in school buildings	50-Years	One room of the school	A simpli5ed LCA method has been applied. Starting with the processes involved and the components used during the construction of the school building, the upstream	Andean arid regions in Mendoza, Argentina	Traditional school building
	Birgisdóttir et al. [118]	To evaluate the resource consumption and environmental impacts related to the different stages in the life cycle of a traditional secondary road in Denmark	100-Years	1 km Secondary road	Complete life cycle of the road system and landfilling and leaching phase in the landfill system	Denmark	No building
	Mroueh et al. [119]	Road constructions: use of industrial by-products in road and earth construction	50-Years	1-km-long section of road	Use of resources, atmospheric emissions, leaching to the ground, and other loadings	Finland	No building
	Vidal et al. [122]	To calculate the environmental impacts of different road pavements during their entire life cycle (HMA and zeolite-based WMA, both with and without RAP content)	40-Years	Section of road 1 km long with a width of 13 m and a thickness of the asphalt layer of 0.08 m	Materials, asphalt production, transportation, construction, use, maintenance, and end-of-life	Spain	No building
5. LCEA	Treloar et al. [130]	Extends Treloar et al. 1999 [167], to include analysis of individual materials, items and features within buildings	40-Years	–	Embodied energy analysis	Australia	Residential building: two-story brick veneer suburban dwelling; Commercial building: typical 15 story Melbourne commercial building
	Adalberth [134]	To descry e the method to calculate the energy use during the life cycle of a building	50-Years	–	Production, management and destruction of the building	Sweden	Dwellings
	Adalberth [135]	To calculate the energy use during the life cycle of a building	50-Years	kW h/(m^2 usable floor area · 50 years)	Production, management and destruction of the building	Örebro, Sweden	Three single-unit prefabricated wood dwellings
	Utama and Gheewala [137]	To evaluate the effect of building envelopes on the life cycle energy consumption	40-Years	–	The construction process of the building enclosure and also intermediate	Semarang, Indonesia	Middle class single landed houses

Table 6 (*continued*)

Section paper	Reference	Scope	Lifetime of the analysis	Functional unit	System boundaries	Location	Building typology
					transportation from quarry to site		
	Utama and Gheewala [138]	To evaluate the effect of building envelopes on the life cycle energy consumption	40-Years	–	The construction of the building envelope and quarrying as well as transportation of materials	Jakarta, Indonesia	Upper class high rise residential buildings
	Cole and Kernan [139]	To evaluate the total life-cycle energy use of buildings	50-Years	–	Total life-cycle energy use	Vancouver and Toronto, Canada	Three-story, generic office building
	Suzuki and Oka [140]	To estimate the energy consumption and CO_2 emissions in each step of the life cycle of buildings	40-years	–	Construction, operation, Maintenance, and renovation	Japan	Several office buildings
	Mithraratne and Vale [141]	To describe a method for LCA based on the embodied and operating energy requirements and LCC of buildings	100-Years	MJ/m^2	Total impact of the building in terms of energy and cost	Auckland, New Zealand	Light-weight timber framed house; concrete timber house, superinsulated light-weight house
	Winther and Hestnes [142]	To compare total energy use during the lifetime in five versions of the same dwelling, with different insulation levels, different ventilation strategies, and different energy saving equipment	50-Years	kW/m^2	Embodied energy, operating energy, and total energy	Hamar, Norway	Wooden row house dwelling
	Thormark [143]	To analyse the recycling potential of a low-energy dwelling in Sweden and to relate the recycling potential to the energy used for production and operation of the building	50-Years	kW/m^2	Embodied energy, energy need for operation and recycling potential	Gothenburg, Sweden	20 low-energy apartments in four two-story rows
	Venkatarama Reddy and Jagadish [147]	Provide information to help in selecting energy efficient building technologies and building systems based on embodied energy thereby reducing cost of materials as well as CO_2 emission into atmosphere.	–	Energy/100 m^2	Energy consumption in building materials; energy in transportation of building materials; energy	India	Different types of buildings and systems
	Shukla et al. [148]	To develop a simple methodology to calculate embodied energy of an adobe house	40-Years	GJ per 100 m^2 built-up area	Embodied energy	Solar Energy Park, Indian Institute of Technology Delhi, New Delhi, India	Adobe house
	Thormark [149]	To analyse the environmental effects of the use of recycled materials in buildings	–	Whole building	All life cycle phases	Sweden	Single-family dwelling with a large proportion of reused building materials and components and recycled materials
	Peuportier [151]	To use LCA and LCEA in buildings	80-Years	Whole building	All life cycle phases	France	Single family houses: the present construction standard in France (reference), a solar and a wooden frame house
	Marceau and VanGeem [153]	To compare the environmental impacts of a concrete house to those of a wood-frame house	100-Years	A single-family house	Extraction and manufacturing of materials, construction, occupancy, and maintenance	Miami, Phoenix, Seattle, Washington, and Chicago, USA	Single-family house with two types of exterior walls: wood framed and insulating concrete form
	Xing et al. [154]	To identify and quantify the energy consumption and environmental emissions during all life-cycle phases of two typical office buildings	50-years	1 m^2 Building area	Energy, greenhouse gases and principal pollution emissions	Shanghai, China	Typical office buildings: steel and concrete-construction

Table 6 (*continued*)

Section paper	Reference	Scope	Lifetime of the analysis	Functional unit	System boundaries	Location	Building typology
	Kua and Wong [155]	Analysis of consumptions of entire buildings	30-Years	–	Extends the traditional system boundary drawn for a whole-building life cycle assessment to include the management of wastes produced during building operations	Singapore	Multi-storied commercial building
	Peuportier et al. [157]	To evaluate the energy and environmental benefit of the passive house concept	50-Years	Whole building	Fabrication of materials, construction, maintenance, dismantling and waste treatment	Picarcy, France	Two attached two-story passive houses
	Proietti et al. [158]	To analyze the benefits due to the use of recycled materials, a solar PV (during the utilization years) and the final demolition of the building	70-Years	One-square meter of living area per a period of 1 year	All life cycle phases: acquisition and production of materials, on-site construction and use/maintenance, demolition and material disposal	Perugia, Italy	Passive house "Fontana": detached family house
	Thiel et al. [159]	To analyzed the environmental impacts of the materials phase of a net-zero energy building	50-Years	The entire CSL building	Material extraction and product processing and manufacturing	Pittsburgh, Pennsylvania, USA	Center for Sustainable Landscapes: three-story educational, research, and administrative office net-zero building
	Monahan and Powell [160]	To conduct a partial LCA, from cradle to site of the construction, of a low energy house constructed using an offsite panelized modular timber frame system	–	The external, thermal envelope of a 3 bedroom, semi-detached house with a total foot print area of 45 m^2 and a total internal volume of 220.5 m^3	Cradle to site emissions from materials and products used in construction, final transport of the materials and products to site, materials waste produced on site, transportation of waste to disposal, fossil fuel energy used on site during construction and in manufacture of MMC components	Lingwood, Norfolk, UK	Semi-detached low energy affordable house
	Huberman and Pearlmutter [161]	To evaluate the influence of different building material configurations on the energy-efficiency of a desert building in Israel	50-Years	The service provided by four student apartments of 28 m^2 each	Embodied and operational energy	Sede-Boqer campus of Ben-Gurion University, Negev desert, Israel	Part of a student dormitory complex designed with a number of passive heating and cooling features
	Aye [162]	To quantify the potential life cycle environmental benefits of prefabricated modular buildings in order to determine whether this form of construction provides improved environmental performance over conventional construction methods	50-Years	Whole building	Embodied and operational energy	Australia	Eight-story, multi-residential prefabricated building
	Gong et al. [163]	Types of framework structures of buildings	50-Years	The three material building designs	All life cycle	Beijing, China	Three types of residential buildings with framework structures: concrete framework construction, light-gauge steel framework construction, and wood framework construction
	Gustavsson and Joelsson [164]	To compare buildings and their energy supply systems using a bottom-up approach, to gain a detailed understanding of production and operation energy alternatives, and facilitated comparisons	50-Years	One square metre of produced and operated building area (total area inside outer walls)	Production and operation phases from a primary energy perspective	Odensala, Lindas, Vaxjo, and Karlstad, Sweden	Five buildings of different types, modified to give a total of 11 case study buildings

Table 6 (*continued*)

Section paper	Reference	Scope	Lifetime of the analysis	Functional unit	System boundaries	Location	Building typology
		between various building and supply systems					
6. LCCA	Nässén et al. [166]	To evaluate net present costs and carbon balances over the life-span of specific building frames with different materials composition	100-Years	Whole building	Energy fluxes, CO_2 balances and costs	Wälludden, Sweden	Two four-story building: a wood framed and concrete-framed version

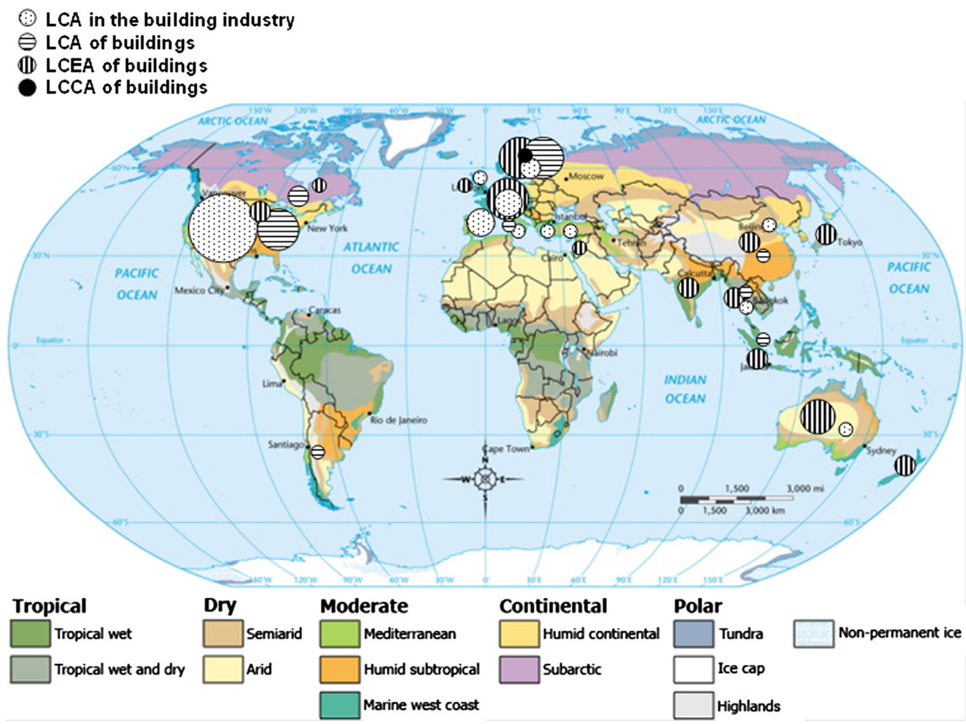

Fig. 8. Summary of the studies considered in this review, organized by areas of assessment and type of study carried out (size of circles represents the amount of studies carried out).

LCA and LCEA papers. Finally, only one LCCA of a building could be found.

Acknowledgements

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